

Interaction of misaligned magnetospheres in the coalescence of binary neutron stars

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We study the dependence of the electromagnetic luminosity—produced by interactions of force-free magnetospheres—on dipole inclinations in binary neutron star systems. We show that this interaction extracts kinetic energy from the system and powers a Poynting flux with a strong dependence on the dipole orientations. This dependence can be linked to the reconnection and redistribution of magnetic field as the stars interact. Although the details of the Poynting luminosity are very much dependent on the orientation, all the cases considered here nevertheless radiate a large Poynting flux. This robust emission suggests that the pre-merger stage of binary neutron star systems can yield interesting electromagnetic counterparts to gravitational wave events.

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I. INTRODUCTION

Binary neutron stars are one of the primary sources of detectable gravitational radiation expected in the next generation of gravitational wave interferometers LIGO/VIRGO/KAGRA [1–3]. Moreover, these systems are also among the strongest candidates for observable neutrino production and energetic electromagnetic output in stellar mass systems, and thus they represent exciting possibilities for upcoming multimessenger astronomy (e.g. [4–6]).

Through the combined efforts of the numerical relativity and astrophysics communities, considerable knowledge has been gained about the expected characteristics of the gravitational waves produced in binary neutron star mergers. Bearing in mind that a thorough exploration of the physical parameter space is still not at hand, several issues have been largely addressed. For instance, much work has studied the dependence of gravitational waves on total mass, mass ratio, and, to some extent, the equation of state (see e.g. [7–10]). Recently, simulations within full general relativity have also begun providing important clues into the dependence on neutron star magnetization [11–16] and cooling [17–19].

In addition to the dynamics and gravitational wave production, the exploration of possible electromagnetic counterparts that complement gravitational wave observations is particularly intriguing. Recently we demonstrated that the interaction between the magnetospheres of each neutron star in a binary can radiate considerable electromagnetic energy [14, 16]. This work used a novel resistive Magneto-HydroDynamics (MHD) approach to describe the magnetic field within the disparate regimes inside and outside each star. Within the star, the approach adopted the ideal MHD limit while the force-free approximation described the magnetospheres. This work started with each star having an initial dipole field either aligned or anti-aligned with the orbital angular momentum and found a powerful Poynting luminosity produced

as the stars orbited. Such a large luminosity provides the tantalizing possibility of powering electromagnetic counterparts to gravitational waves from the system. The Poynting flux for equally magnetized stars with either aligned or anti-aligned dipole moments was found to be collimated along the polar region. In contrast, when one star was unmagnetized or barely magnetized with respect to the other, the Poynting flux was mainly directed around the equatorial region. Naturally, generic systems are not expected to have such a preferred alignment of dipole magnetic moments, and thus the study of different scenarios is important. We address this question here by considering misaligned dipoles in binary neutron star mergers.

According to the standard formation channel, a binary neutron star system is formed from a primordial binary through a sequence of complex processes [20–23]. The first of these processes is a supernova explosion of the more massive star once it evolves off the main sequence and through its giant phase. The remnant of such an explosion becomes the first NS of the binary, generally more massive than the second NS and with a potential recoil. Subsequently, the secondary star then evolves off the main sequence and, ultimately, explodes as a supernova becoming the second NS.

The discovery of strongly relativistic, binary pulsars provides strong support for the formation channel described above. Any kicks provided by the supernovae are important not only in determining whether the binary survives, but also in determining the properties of the resulting binary. In particular, kicks can tilt the orbital plane of the binary and misalign the individual spins of the NSs [24]. Furthermore, it has been empirically argued [25, 26] that the angle between the magnetic and spin axes of NSs may not be random but instead correlated to each other. The orientations of the magnetic moments in generic binaries are therefore plausibly arbitrary.

In this work, we consider different orientations of

the stellar magnetic dipoles and compute the resulting Poynting flux characteristics as the stars coalesce¹. In addition to a strong flux of electromagnetic energy produced due to magnetosphere interactions, our results indicate that one can bracket the expected luminosities from general configurations. Our simulations focus primarily on the last orbits before the merger in which the dynamics are most rapid and violent and simplified analytic models are not applicable. Additional insight comes from modeling the behavior of a magnetized star moving within the field of a distant star, modeled here as a constant external field. While such an approach is only valid when the stars are well separated, it serves to generalize well-known results with the unipolar inductor.

This work is organized as follows, in Sec. II we present theoretical arguments and estimates for the possible electromagnetic luminosity induced by the system. Sec. III summarizes briefly the evolution equations describing the magnetized neutron stars, as well as our numerical setup. Our results are presented in Sec. IV, followed by conclusions in Sec. V.

II. THEORETICAL ESTIMATES

To estimate the power of the systems studied here, we begin by considering the process of *unipolar induction* [28]. Within the simple model discussed in Ref. [29], the electromagnetic power radiated by an unmagnetized, perfectly conducting neutron star moving through a magnetically dominated medium (i.e., such that the Alfvén speed approaches the speed of light) can be estimated by

$$\mathcal{L}_{\text{Alfven}} \approx \frac{v^2}{2c} B_z^2 R_c^2, \quad (1)$$

where v is the relative velocity between the neutron star and the external magnetic field of strength B_z , and R_c is the radius of the neutron star.

We apply this estimate to a binary, in which we identify the moving star as the unmagnetized companion. The primary star in this system is then the source of the magnetic field external to the companion. As such, we assume a dipole field for the primary so that $B_z = B_*(R_*/a)^3$ where B_* is the magnetic field strength at the pole of the primary, R_* its radius, and a the binary separation. Substitution for B_z into Eq.(1) yields [30]

$$\mathcal{L}_{\text{Alfven}} \approx \left(\frac{v}{c}\right)^2 \frac{B_*^2 R_*^6 R_c^2 c}{2a^6}, \quad (2)$$

which is consistent with the dissipation rate estimated in Ref. [31] by using a circuit model for the magnetic interactions of such a binary.

Although this estimate applies only to binaries with an unmagnetized companion, neutron stars in binaries are unlikely to have a vanishing magnetic moment. It is however possible to generalize the previous luminosity estimate to systems with a relatively weaker magnetized companion with respect to the primary's magnetization as follows. Consider the companion having a (dipolar) magnetic field. In the electrovacuum case, the strength of this field will dominate over the external one (induced by the primary) roughly when the following condition (centered at the location of the companion) is satisfied

$$B_c \left(\frac{R_c}{r}\right)^3 \sqrt{\frac{1 + 3\sin^2(\pi/2 - \theta)}{4}} > B_z \quad (3)$$

with B_c the magnetic strength at the pole of the companion and θ the angle between the stellar magnetic moment and the radial vector to a given point. Also, for simplicity B_z is the strength of a constant field, representing the effect of a widely separated primary star. Neglecting the angular dependence, we call the surface around the companion where the internal magnetic field balances the external field a *screening sphere* for the following calculation. The radius R_m of this screening sphere is just

$$R_m \approx R_c s_z^{1/3}, \quad s_z \equiv B_c/B_z. \quad (4)$$

This is applicable as long as $R_m \gg R_c$ or $s_z \gg 1$, but in the case of an unmagnetized companion one must set $R_m = R_c$ in order to recover the Alfvén radiation power of Eq.(1). Thus, to account for both limits, we slightly modify Eq.(4) to recover the appropriate values for both $s_z \gg 1$ and $s_z \ll 1$

$$R_m \equiv R_c \max\left(1, s_z^{1/3}\right). \quad (5)$$

We now substitute R_m for the radius of the companion R_c in Eq.(1) to get an estimate of the Alfvén radiation power of a magnetized star moving through an external field

$$\mathcal{L}_{\text{Alfven}} \approx \frac{v^2}{2c} B_z^2 R_c^2 \max\left(1, s_z^{2/3}\right). \quad (6)$$

We stress that this estimate relies on several approximations. First, we have neglected the angular dependence in Eq. (3), which might modify the screening radius by at most a factor 2 (i.e., when the magnetic moment of the companion is perpendicular to the external magnetic field). Second, Eq. (5) is only valid in the asymptotic limits $s_z \gg 1$ and $s_z \ll 1$, and so deviations in the luminosity are naturally expected when $s_z \approx 1$. Finally, the luminosity in Eq. (6) results from rather simple arguments which, for example, do not consider reconnection or deformation of field lines. We expect that these corrections will not modify the dependence $s_z^{2/3}$ for large s_z , but, as we show via simulations later, the intensity of the resulting luminosity can be affected by their impact on the proportionality factor (see e.g. Fig 2).

¹ Tilted magnetic fields have also been considered in black hole-neutron star binaries to assess their role in inducing toroidal magnetic configurations in the resulting accretion disk [27].

Returning to a binary system, again neglecting the angular dependence, we can similarly equate the fields of the primary and companion

$$B_* R_*^3 / (a - R_m)^3 = B_c (R_c / R_m)^3. \quad (7)$$

Assuming that the two stars have similar radii $R_* \approx R_c$ and that they are far apart $a \gg R_m$, Eq.(7) leads to $R_m \approx a(B_c/B_*)^{1/3}$. Again placing a lower limit on the effective radius, we have $R_m = \max[R_c, a(B_c/B_*)^{1/3}]$. We generalize Eq.(2) obtaining the Alfvén radiation power for a magnetized binary by substituting R_m for R_c . For small separations, $R_m \approx R_c$ and this generalized power hardly differs from Eq.(2). However, for large separations the magnetic field of the primary will be small near the companion, and in that limit the luminosity will be

$$\mathcal{L}_{\text{Alfvén}} \approx \left(\frac{v}{c}\right)^2 \frac{B_*^2 R_*^6 s_*^{2/3} c}{2a^4}, \quad s_* \equiv B_c/B_*, \quad (8)$$

which enhances the original Alfvén power by a factor $(a^2/R_c^2)s_*^{2/3}$.

Let us stress again that this result is only valid for companions with weaker magnetizations (with respect to the primary) and for binaries in a quasi-adiabatic stage. Assuming Keplerian orbits $v^2 \propto a^{-1}$ for simplicity, we can see from Eq.(2) that when the companion is unmagnetized the luminosity scales as a^{-7} . On the other hand, when the two stars are magnetized, the radiated electromagnetic luminosity behaves differently because of the interaction between each star with the field of the other. This interaction depends strongly on the relative orientation of the dipole fields of the stars, as we discuss later. For weakly magnetized companions, it follows from Eq.(8) that the luminosity has a softer dependence a^{-5} . Finally, for comparable magnetizations and with dipole moments aligned or antialigned, we found in previous work [14, 16] that in the last orbits $\mathcal{L} \propto a^{-3} - a^{-1.5}$. These three estimates demonstrate a clear influence by the stellar magnetization on the binary luminosity. Notice as well that as the orbit tightens and the stellar accelerations increase, an additional contribution (a “Larmor-type” term) becomes non-negligible [32] and may contribute to soften the luminosity dependence on a .

III. NUMERICAL APPROACH

Our aim is to study the behavior of magnetically dominated plasma surrounding single or binary magnetized neutron stars. The complexity of these problems demands numerical simulations that incorporate general relativity and relativistic, resistive magnetohydrodynamics [33] (see [34] for a related approach not relying on resistive MHD). We have developed such a framework and applied it recently to study the collapse of neutron stars [33] and magnetospheric interactions of magnetized binary neutron stars with aligned/anti-aligned magnetic moments [14, 16].

Our approach solves the Einstein-Maxwell-hydrodynamic equations to model strongly gravitating compact stars and the effects of a global electromagnetic field. Inside the star, the magnetic field is modeled within the ideal MHD limit, transitioning to the force-free limit outside the stars. This transition is achieved, in our resistive MHD framework, by a prescription for the (anisotropic) conductivity tensor that depends on the fluid density (see [33] for details). We adopt the BSSN formulation [35, 36] of the Einstein equations as described in [37].

We use finite difference and finite volume techniques on a regular, Cartesian grid to discretize the system [38, 39]. The geometric fields are discretized with a fourth order accurate scheme satisfying the summation by parts rule, while High Resolution Shock Capturing methods based on the HLLE flux formulae with PPM reconstruction are used to discretize the fluid and the electromagnetic variables [40, 41]. The time evolution of the resulting equations must deal with the presence of stiff terms arising from the resistive MHD scheme in the evolution of the electric field in Maxwell’s equations. Such terms are efficiently handled with a third order accurate IMEX (implicit-explicit) Runge-Kutta scheme, as described in [33, 42, 43].

To ensure sufficient resolution is available in an efficient manner, we employ adaptive mesh refinement (AMR) via the HAD computational infrastructure that provides distributed, Berger-Oliger style AMR [44, 45] with full sub-cycling in time, together with an improved treatment of artificial boundaries [46]. In this work we only use fixed mesh refinement (FMR), with refinement boxes covering the regions surrounding the stars. The grid resolutions adopted here are the same as those used previously to obtain convergent evolutions [14, 16]. We confirm this convergence here by varying the resolution by 20% for one of the most extreme binary configurations (i.e., the P/P case defined in Section IV B) and finding agreement in the obtained luminosities to within $\approx 2\%$.

IV. RESULTS

Here we describe the details of our numerical studies of magnetized neutron stars. We begin with a magnetized star boosted with respect to an external magnetic field. It is natural to generalize the analysis of this system to the case of a binary system with a magnetized primary and a weakly magnetized companion. We then study the effects of varying the orientation of stellar magnetic moments (with equal magnitude), on the resulting Poynting luminosity in a binary system.

A. Boosted Magnetized Neutron Star

Consider a non-rotating, magnetized neutron star moving with constant velocity with respect to a uniform,

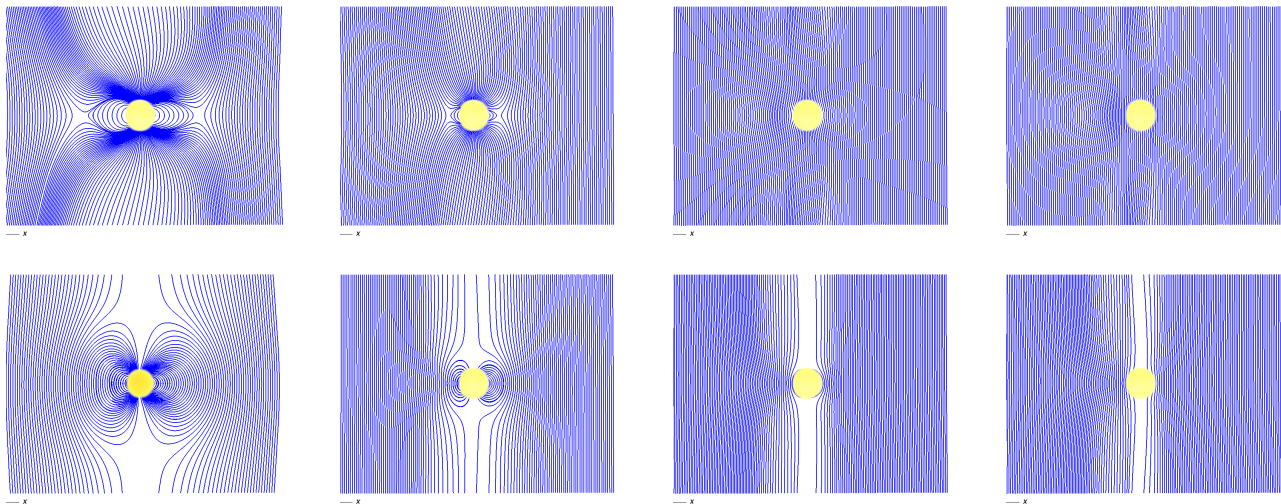


FIG. 1: Magnetic field lines (blue) and stellar density (yellow) for a star boosted to the right with speed $v/c = 0.05$, once the system reaches a quasi-stationary state (which depends primarily on the velocity of the star; roughly 5ms for these cases). In the **top** panel, the magnetic moment is anti-aligned with an external magnetic field allowing for reconnection in the polar regions above and below the star. The initial magnetic strength ratio is given by $s_z \equiv B_c/B_z = \{-100, -10, -1, -0.1\}$ from left to right. In the **bottom** panel, the stellar magnetic moment is aligned with an external magnetic field, leading to opposing field lines in the polar regions and a Poynting luminosity smaller than the anti-aligned case for the same magnitudes $s_z = \{100, 10, 1, 0.1\}$ (see the top panel of Fig. 2).

external magnetic field. This system models a weakly magnetized star moving slowly within the field produced by a distant, primary star. Because the emitted luminosity can be rescaled by the external magnetic field B_z , a convenient way to parameterize the results is with the dimensionless ratio $s_z \equiv B_c/B_z$, where B_c is the magnetic field strength at the pole of the boosted star. For simplicity, we assume that the stellar magnetic moment is either aligned or anti-aligned with the external, asymptotically constant magnetic field B_z .

We evolve with a range of magnetizations $|s_z| = \{100, 10, 1, 0.1\}$ and monitor the system (luminosity, field topology, etc.) until the star reaches a quasi-steady configuration. Examples of the relaxed configurations are shown in Fig. 1 for $s_z < 0$ (top) and $s_z > 0$ (bottom). The figure makes clear that positive and negative values of s_z yield significantly different behavior. For negative s_z , the polar magnetic field reconnects with the external field, effectively connecting the star magnetically to the asymptotic field. As a consequence of this connection a direct path for Alfvén radiation is induced as the stellar motion disrupts the external field.

In contrast, for positive s_z , the direction of the stellar field at the polar region is opposite to that of the external field. This opposition creates a roughly spherical region in which the external field is screened. The resulting deformation of the field lines around this region produces Alfvén waves with a released power smaller than the negative case.

The total luminosity as a function of $|s_z|$ is shown in

the top panel of Fig. 2. As anticipated analytically, it displays a polynomial growth dependence as $|s_z|^{2/3}$ for $s_z \gg 1$, and reduces to the unmagnetized case for $s_z \ll 1$. Around $s_z \approx 1$ neither of these limits is well satisfied and we expect departures from our simplified expression. Interestingly, a stronger luminosity results for $s_z < 0$, suggesting that the continuous reconnection occurring in the stellar polar regions yields a more powerful Poynting flux. We also confirm that the Alfvén power is proportional to v^2 by studying a magnetized star with fixed $s_z = 1$ and different boost velocities $v/c = \{0.025, 0.05, 0.075\}$, as shown in the bottom panel of Fig. 2. These velocities have been chosen bearing in mind that when stars in a binary are separated by about 400km their velocities are roughly $v/c \sim 0.1$. At this (or larger) separation, to leading order the star can be regarded as moving through the field produced by the other without strong, non-linear effects playing a role in the dynamics.

B. Binary neutron stars

We now turn our attention to binary neutron stars. For simplicity we have adopted a setup almost identical to the one described in [14, 16], except for the orientation of the magnetic dipole moments of the stars. We thus consider a binary of identical, irrotational neutron stars with baryonic mass $M = 1.62M_\odot$ and radius $R_* = R_c = 13.6\text{km}$. The binary is initially in a quasicircular orbit with angular velocity $\Omega_o = 1.85\text{rad/ms}$ and separation $a = 45\text{km}$.

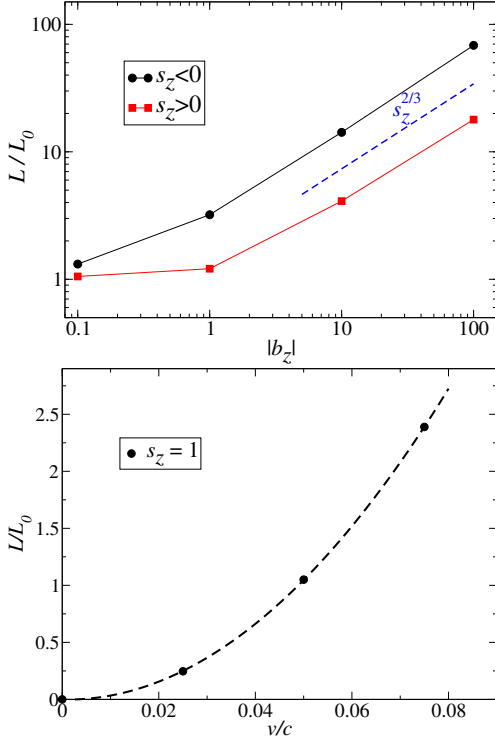


FIG. 2: *Top-panel*: Luminosity as a function of $s_z \equiv B_c/B_z$ for a boosted star with $v/c = 0.05$ for both anti-aligned and aligned magnetic dipoles. Notice that while both cases have approximately the same dependence on s_z , the anti-aligned case is more luminous. *Bottom-panel*: Luminosity as a function of the velocity of the boosted star with $s_z = 1$ (aligned case). Also shown is a fit (dashed curve) assuming a quadratic dependence on velocity ($\propto v^2$). For concreteness we have normalized the luminosities in both plots by $L_0 \equiv L(s_z = 0, v/c = 0.05)$.

Consistent initial geometric and matter configurations for this system are obtained with the LORENE library [47], which adopts a polytropic equation of state $P = K\rho^\Gamma$ with $\Gamma = 2$ and $K = 123G^3M_\odot^2/c^6$ (notice that we use units with $G = c = M_\odot = 1$). The binaries merge at $t \approx 7$ ms, and they are evolved for 2–3ms afterwards. In what follows, for concreteness, we shift $t = 0$ to the time that the stars touch. During the evolution, the fluid is modeled with an ideal gas equation of state which allows for the formation of shocks.

The magnetic moment μ_i describes a dipolar magnetic field B^i in the comoving frame of each star. In our previous work [14, 16] we have considered scenarios in which the magnetic moment is aligned with the orbital angular momentum, i.e. $\vec{\mu} = \mu\hat{k}$ (with k the unit vector along the z axis and parallel to the angular momentum). Here we consider less idealized cases in which the magnetic moment can be perpendicular to the orbital angular momentum, i.e. $\vec{\mu} = \mu\hat{i}$ (with i the unit vector along the x axis on the orbital plane). Notice that the radial magnetic field at the pole of the star B_* is related to the magni-

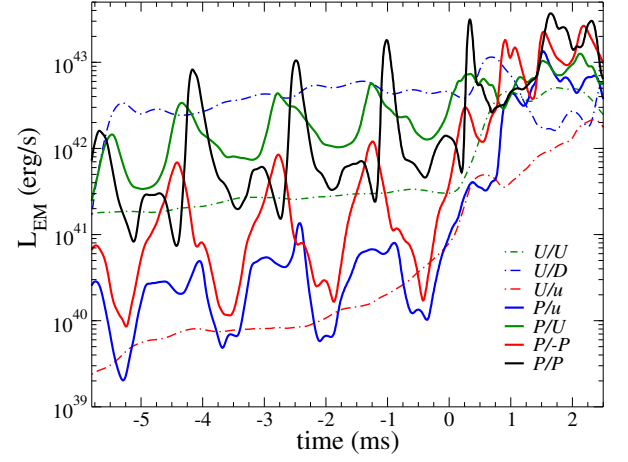


FIG. 3: Luminosities for different magnetic dipole configurations in a binary neutron star system, shifted in time such that $t = 0$ denotes first contact between the stars. The configurations studied here are displayed with solid lines, whereas those studied previously in [14, 16] are also included (dot-dashed lines) for reference. Note that the U/u and U/D configurations roughly bracket the values obtained in the misaligned cases.

tude of the magnetic moment by the relation $\mu = B_*R_*^3$. In all simulations considered, we adopt $B_* = 1.5 \times 10^{11}$ G, a value which, while admittedly high, is within the expected range for realistic neutron stars in binaries. The initial electric field is obtained from the ideal MHD condition.

We consider a range of configurations with at least one of the stars containing a magnetic moment perpendicular to the orbital angular momentum:

- P/u : one-dominant, perpendicular case $\mu_x^{(1)} = 100\mu_z^{(2)} = \mu$, where one of the magnetic moments is aligned with the orbital angular momentum but having a much smaller magnetization than the perpendicular one.
- P/U : perpendicular-aligned case $\mu_x^{(1)} = \mu_z^{(2)} = \mu$, where one of the magnetic moments is aligned with the orbital angular momentum and the other is perpendicular to it.
- $P/-P$: perpendicular-antiperpendicular $\mu_x^{(1)} = -\mu_x^{(2)}$, where both magnetic moments are anti-parallel to each other and perpendicular to the orbital angular momentum.
- P/P : perpendicular-perpendicular $\mu_x^{(1)} = \mu_x^{(2)}$, where both magnetic moments are parallel to each other and perpendicular to the orbital angular momentum.

We recall that in our previous study we have already considered the following three cases with magnetic moments parallel to the orbital angular momentum:

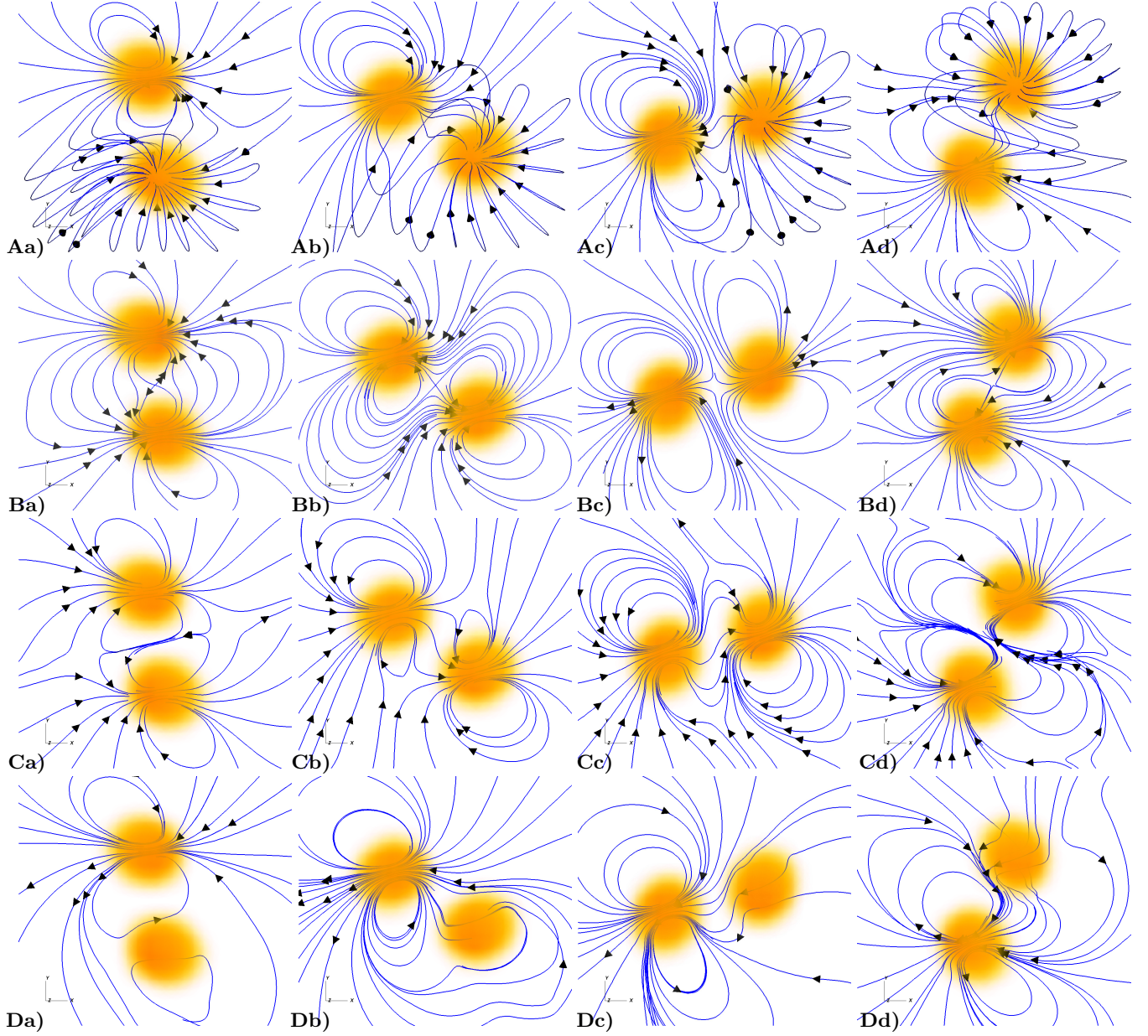


FIG. 4: Stellar density (yellow) and magnetic field lines (blue) seeded on the orbital plane. The columns **a**, **b**, **c**, **d** display the configurations at times $t \approx \{-3.6, -3.2, -2.8, -2.2\}$ ms, where time intervals between successive columns describe roughly one eighth of an orbit. The radius of each star is $R = 13.6$ km and the binary initial separation is $a = 45$ km. **Row A**: magnetic dipoles perpendicular/parallel to the orbital (P/U), **Row B**: magnetic dipoles parallel to the orbital plane (opposite orientations) ($P/-P$), and **Row C**: magnetic dipoles parallel to the orbital plane (same orientations) (P/P), and **Row D**: non-magnetized/magnetized stars with magnetic dipole in the orbital plane (P/u). Notice that field lines depicted in Row A appear to cross other lines, but they actually leave the orbital plane and do not cross (see Fig. 5).

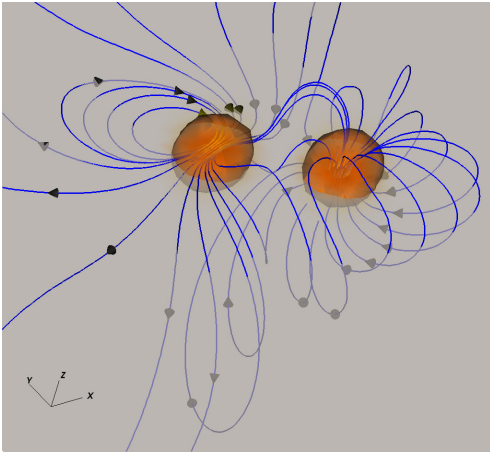


FIG. 5: Three-dimensional arrangement of field lines for the P/U case, roughly 3ms before merger. We have made the orbital plane translucent (displayed in grey) to aid in distinguishing sections of the field lines lying above from those below the $z = 0$ plane (the latter darker in color). Notice this case has field lines that naturally venture off the orbital plane.

- U/U : aligned case $\mu_z^{(1)} = \mu_z^{(2)} = \mu$,
- U/D : anti-aligned case $\mu_z^{(1)} = -\mu_z^{(2)} = \mu$,
- U/u : one-dominant, aligned case $\mu_z^{(1)} = 100 \mu_z^{(2)} = \mu$.

For the rest of the paper, we refer collectively to these three cases as the *aligned* cases for simplicity because both magnetic dipoles are perpendicular to the orbital plane, despite the fact that the U/D case is anti-aligned with the orbital angular momentum.

Our numerical domain extends to 320 km in each direction and contains five, centered FMR grids with decreasing side-lengths (and twice as well resolved) such that the highest resolution grid has $\Delta x = 300$ m and extends up to 58 km, covering both stars and the inner part of the magnetosphere. Within this setup, we study the four cases described above: P/u , P/U , $P/-P$, and P/P and compare with those previously studied U/U , U/D and U/u .

Of particular relevance is the behavior of the Poynting flux resulting from the dynamics and its dependence on the magnetic dipole orientation. The luminosities, displayed as a function of time in Fig. 3, are computed by integrating the outgoing Poynting flux on a surface located at $R_{\text{ext}} = 180$ km. We also extract this quantities at two further radii to confirm the expected r^{-2} asymptotic behavior of the Poynting flux. As evident in the figure, the total luminosity differs across all cases considered; not only does the strength vary depending on orientation but also temporal modulations are induced. The luminosities are roughly periodic, accompanied by an overall increase as the orbit tightens.

As we discuss in more detail below, these temporal modulations appear because of complicated dynamics between the stellar magnetospheres. In particular, our results indicate that the local maxima (peaks) in the luminosity arise, for both stars equally magnetized (i.e. the cases P/U , P/P , $P/-P$), at the times when the magnetic fields emanating from each star reconnect. In other words, these three cases are roughly cyclic, and at one point in the cycle, the field lines from one star reconnect with those of the other, causing a peak in the luminosity. Subsequent to the reconnection, the lines elongate until they must reconfigure to begin a new cycle.

The magnetic field configurations and the stellar density are shown at different representative times in Fig. 4. In order to illustrate the relationship between the field dynamics and the oscillations in the luminosity, we identify particular physical events, such as when the stars have severely stretched their connecting field lines or when reconnection between the stars reconfigures those connecting lines. By accounting for the propagation time to the extraction surface, we establish certain correlations for each case as described below.

We begin with the P/U case, which is the most complex one as in that the bilateral symmetry ($z \rightarrow -z$) is broken and the field lines cross the orbital plane (see Fig. 5). In this case, strong reconnections arise when the magnetic moment perpendicular to the angular orbital momentum (P) points away from the other star (see Fig. 4-Ac). At such a stage, short field lines from the U star connect with the P star as shown in Fig. 5. These tight, linking field lines are subsequently stretched until reconnection re-establishes the tight linking. This reconnection is thus expected to occur with every half-orbit and such a periodicity is evident in the total luminosity for this case as shown in Fig. 3.

Let us turn now to the $P/-P$ case. Here, when the polar regions face each other, the field lines from each star are oppositely-directed resulting in large deflections (see Fig. 4-Bc). A quarter of an orbit later—when the “lateral” sides of each star face each other—the field lines emanating from one star towards the other can reconnect with those of the companion star (see Fig. 4-Ba). Here again, as the orbit proceeds, these lines stretch until they must reconfigure by reconnection to repeat the cycle. These reconnection events give rise to the observed local maxima, which occur twice per orbit. The behavior exhibited by the P/P case is in clear contrast to the $P/-P$ case. Namely, in this binary, it is when polar regions face each other that fields emanating from one star can reconnect with those entering the companion (see Fig. 4-Cc). As the orbit proceeds, the lines stretch and reconfigure to repeat the cycle. Consequently the geometry of the $P/-P$ case is such that the tightest configuration of field lines occurs a half-orbit later than the corresponding tightest configuration of the P/P case. This offset is also evident between the local peaks in the two luminosities in Fig. 3.

In addition to the oscillatory features, the overall luminosities of these two cases ($P/-P$ and P/P) are roughly

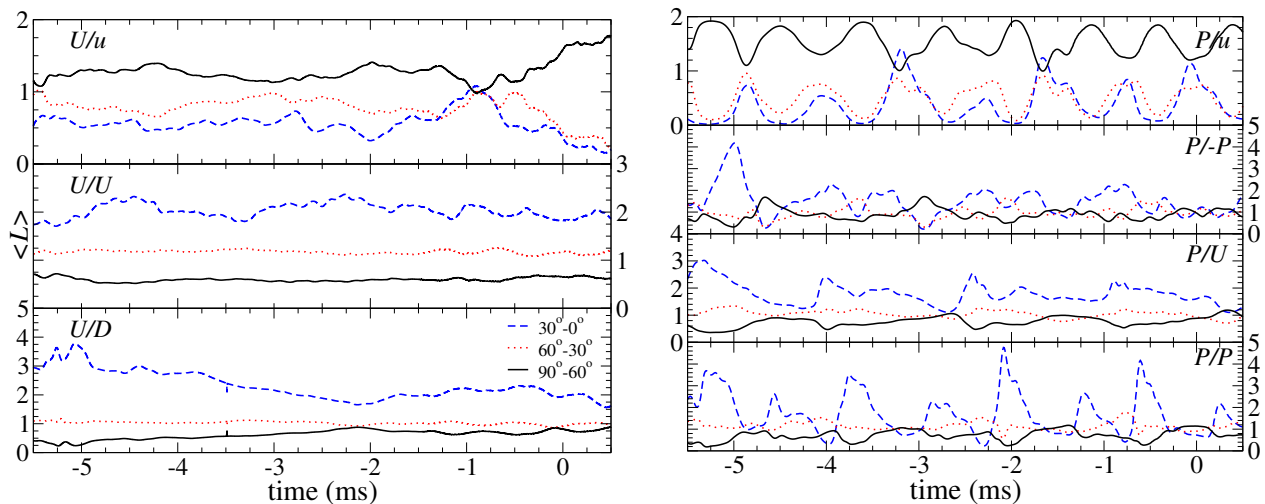


FIG. 6: *Left-panel*: Average luminosity per solid angle $\langle L \rangle \equiv L_{\langle \theta_1, \theta_2 \rangle} / [2\pi(\cos \theta_2 - \cos \theta_1)]$, normalized by the total luminosity density $L_T/(4\pi)$, for the three aligned cases: U/U (first row), U/u (second row) and U/D (bottom row). Notice that in the U/U and U/D cases, the radiation patterns appear collimated, while the U/u case radiates mostly close to the orbital plane of the binary. *Right-panel*: Average luminosity per solid angle for the four misaligned cases: P/u (first row), P/U (second row), $P/-P$ (third row) and P/P (bottom row). The radiative patterns of these configurations are more dynamic than those in the left panel (see also Fig. 7).

an order of magnitude different. Similar to the U/U and U/D cases, we attribute this difference to the fact that the more luminous of the pair belongs to that with the “tightest” magnetic configuration, where by “tightest” we roughly mean the minimum (electrovacuum) potential energy $U = -\vec{\mu}_1 \cdot \vec{B}_{2|1} - \vec{\mu}_2 \cdot \vec{B}_{1|2}$ achieved by the two dipoles during their orbit (with $B_{i|j}$ denoting the magnetic field induced by the star i at the location of star j). Just as the U/D case has less potential energy than the U/U case and is more luminous, we find here that the P/P case is similarly more luminous than the $P/-P$ case.

The luminosity of the P/u case also displays temporal modulations, but notably the local maxima at early times seem correlated with those of the P/P case. This correlation can be understood by first noticing that for the separations considered, the magnetic field in the neighborhood of the weakly magnetized star is dominated by that from the strongly magnetized star. As the u star passes through the region near the polar caps of the strongly magnetized P star, the disruption to the ambient field is maximized (see for instance Fig. 4-De) and it is at these points in the orbit that the luminosity peaks occur. These points occur twice an orbit and geometrically coincide with the configurations of the P/P case which produce peaks in its luminosity.

Interestingly, all obtained luminosities are roughly within the range defined by our previously studied aligned cases [14, 16]; i.e. the U/u and U/D cases represent lower and upper limits. In addition, those previous cases did not show any significant temporal modulation, which arises here as a result of the misalignment of magnetic moments with respect to the orbital angular

momentum. More importantly, inspection of the luminosity per solid angle for the misaligned cases considered here indicates only an episodic collimation of the resulting Poynting flux for all cases (see Fig. 6). This contrasts with the U/U and U/D cases which show a clear, sustained collimation, radiating more strongly within a conical section orthogonal to the orbital plane. The Poynting fluxes for all the cases, projected onto a sphere encompassing the binary, are displayed in Fig. 7 at $t \approx 1.5$ ms before the merger. The observed structures are much more involved than the previously studied aligned cases.

Finally, one may wonder why the U/D and U/U cases considered in the previous paper lack the periodicity shown in the cases here, since their luminosities were previously explained in terms of stretching and reconnection. However, it is important to note that the U/D and U/U cases preserve an approximate azimuthal symmetry as the stars orbit. In other words, the reconnection occurs continuously. In contrast, the orbits of the cases here are marked by different relative dipole orientations at different times in the orbits. The U/D and U/U cases essentially look the same for any point in the orbit.

V. DISCUSSION

We study the interaction of magnetospheres in binary systems in two different magnetization regimes. The first corresponds to a strongly magnetized primary with a weakly magnetized companion at large separations. We extend the analytic estimates for binaries with a single magnetized star, obtained with the unipolar induction model [30, 31, 48], to cases where both stars are mag-

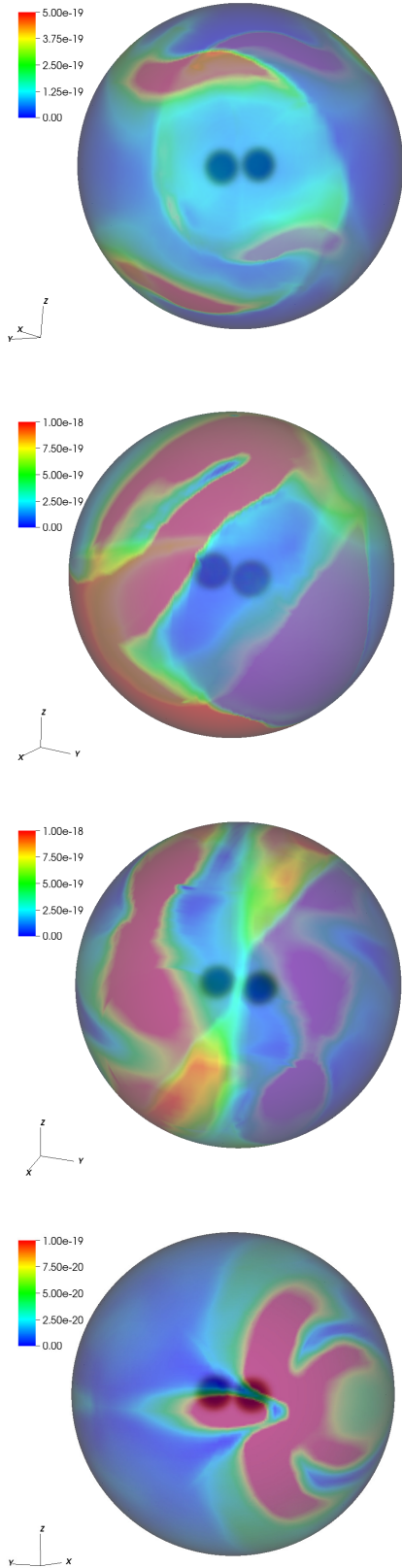


FIG. 7: Poynting flux evaluated on an encompassing sphere at approximately 120km from the binary, roughly $t \approx 1.5$ ms before merger. The P/P (first row), P/U (second row), $P/-P$ (third row), and P/u (fourth row) are shown from top to bottom—in decreasing order of collimation. Notice however, that the more highly collimated emissions are episodic (as shown in Fig.6).

netized. We confirm the validity of this extension by studying a magnetized star boosted with respect to an external magnetic field. This scenario is a reasonable approximation to the dynamics of these binaries at large separations.

In the second regime, we explore magnetosphere interactions in the final orbits prior to merger. We employ numerical simulations, solving the general relativistic resistive magnetohydrodynamics equations to capture the complex dynamics of the binary and its magnetosphere. By comparing our results with previous work [14, 16], we show that magnetospheric interaction extracts kinetic energy from the system and powers a strong Poynting flux for different orientations of the stellar magnetic dipoles. Indeed, the electromagnetic luminosity for all configurations is sizable, giving strong hope for the observation of electromagnetic counterparts to gravitational wave events sourced during the late orbiting stages. In particular, our results show that during these stages, the luminosities present an approximately cyclic temporal oscillation tied to the magnetic field and orbital dynamics. The luminosities for these misaligned configurations (and possibly for generic ones as these represent rather contrasting configurations) are roughly within the range defined by the previously studied aligned U/u and U/D cases, as shown in Fig. 3.

As discussed in detail in [16], the energy radiated during the coalescence of these binary systems can give rise to several promising emission channels. Indeed, the field configuration and dynamics obtained have features clearly tied to models for non-thermal components in pulsars and related systems. As our studies indicate, the resulting Poynting flux is not strongly collimated—and thus could induce isotropic emissions—and its complex time dependence is intimately tied to the field configurations in the stars. The basic premises for non-thermal components in pulsars are present in binaries such as studied here and can contribute to the spectra. In particular, standard estimates for synchrotron self-absorption indicate synchrotron radiation could be observed from radio to gamma rays [49] and bear imprints of the oscillations observed in the luminosities. Further, these BNSs may power an expanding electron-positron wind with a thermal spectra that could be observable in X-ray by ISS-Lobster at distances $10^{0-2}(B/10^{11}G)$ Mpc, depending on the particular configuration of the magnetic moments.

The structure of the magnetic field lines for the misaligned cases—except the P/u case—clearly cycles through repeated configurations involving both stars (reconnections-stretching-deflection), indicating that a simple model of “electric circuits,” with currents flowing along the magnetic field lines, might still be useful for these systems. However, it should be stressed that these are transitory circuits because they are created and destroyed twice per orbit.

Indeed, the maxima in electromagnetic luminosity correlate with the reconnection events that produce a very tight connection via magnetic flux between the stars. For

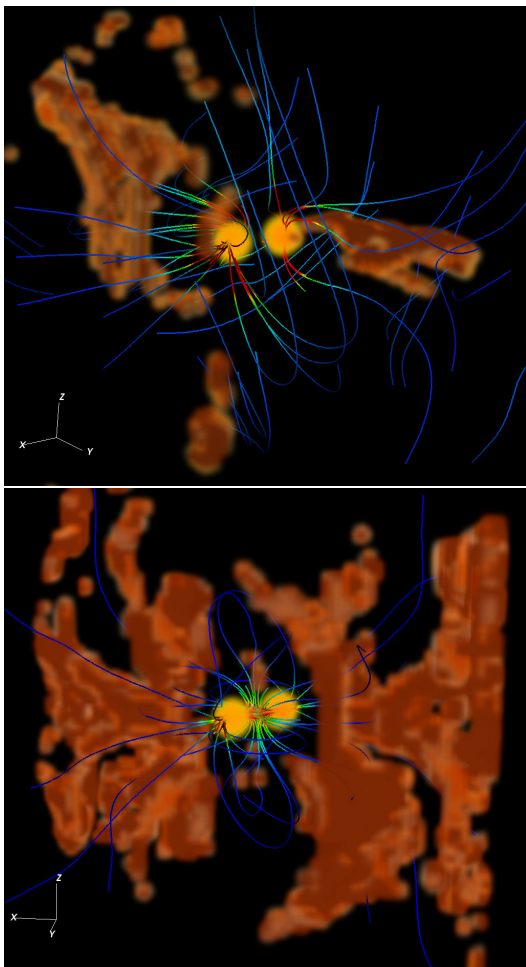


FIG. 8: Current sheets in the P/U (upper panel) and $P/-P$ (lower panel) cases, roughly 1.5ms before merger. The current sheets associated with each star appear on the plane perpendicular to the magnetic dipole crossing roughly through the star itself. Consequently, the current sheets in the P/U case appear both along and orthogonal to the orbital plane, while in the $P/-P$ case current sheets occur only in planes perpendicular to the orbital plane.

the P/P case in particular, the luminosity peaks occur when the dipoles roughly align (i.e. fall along a line) and such an aligned configuration naturally produces a very compact, tight field configuration. As evident in Fig. 3, the maxima in the P/P case are more luminous for those brief moments than any of the other cases.

As in the case of isolated pulsars and aligned dipole configurations in binary systems, current sheets² also arise in the misaligned cases. However, the character of these current sheets is quite different, being much more dynamical and temporal, with an appearance that is re-

² Current sheets have been linked to different emission channels for energetic electromagnetic signals in which synchrotron or inverse Compton scattering may produce gamma-rays [50].

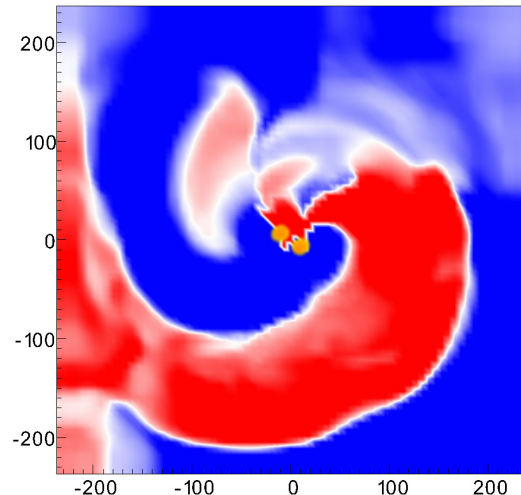


FIG. 9: Polarity of the B_z component (red positive, blue negative) for the P/U case, displayed slightly below the orbital plane ($z = -7.5\text{km}$), roughly 3ms before merger. The “striped” pattern displays a spiral structure that persists during the evolution and rotates with the binary, alternating the polarity at any particular point approximately once per orbit. Similar patterns and dynamics are present for the corresponding components of the magnetic field in the other two orthogonal coordinate planes (i.e. $x-z$ and $y-z$).

current with the orbital period and orbiting with a lag of roughly a quarter orbit with respect to the stars. Examination of the current sheets, such as shown in Fig. 8, suggests that in the neighborhood of each star, one finds current sheets forming in the plane orthogonal to its dipole field and roughly bisecting the star itself. For the P/U case shown in the top panel, current sheets about the star on the left form in a vertical plane whereas the star on the right forms current sheets within the orbital plane. In the $P/-P$ case (bottom panel), both dipoles lie in the orbital plane and current sheets form in two vertical planes that rotate with the stars. The results of the aligned cases of Ref. [14] in which the dipoles are aligned vertically are consistent with this suggestion; the current sheets in those cases generally arose in the orbital plane which is the plane perpendicular to each dipole (see Fig. 1 of Ref. [14]).

Finally, it is interesting to mention that certain features common to both aligned and oblique rotators [51] clearly arise in the P/U case. We observe an alternating polarity in the induced magnetic field configurations, see Fig. 9. As discussed in [52], this behavior may cause strong particle acceleration and generate intense radiation via synchrotron. The phenomenology discussed here, together with results presented in [14, 16], explicitly argue that magnetospheric interaction in binary neutron star systems can produce a strong electromagnetic output prior to merger, regardless of the magnetic moments configurations. Identifying pre-merger counterparts is

important for concurrent detection because the GW frequency of the binary will increase at merger out of the sensitivity band of advanced GW detectors.

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